

## SECTION II.—GENERAL METEOROLOGY.

## THE REGION OF GREATEST SNOWFALL IN THE UNITED STATES.

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## DEEP SNOWFALLS.

California, usually thought of as a land of fruit, sunshine, and flowers, also has within its borders the region of greatest snowfall in the United States. The apparent anomaly is explained by the fact that this State (second in size in the Union) is an empire in itself. Variety is the keynote in all of its physical features, and extreme variety is noticeable in the climate of its various parts. For example, during the year 1913 a temperature of  $-21^{\circ}\text{F}$ . was recorded at Alturas on January 23, while a temperature of  $+134^{\circ}\text{F}$ . occurred at Greenland Ranch on July 10. Moreover, during that same year no measurable amount of rain occurred at Bagdad, Cal., while in the northern part of the State 100 inches of precipitation occurred. Twelve regular and 235 cooperative stations of the United States Weather Bureau are now in operation within the State of California. They extend vertically from Mecca, 185 feet below sea level, to Bishop Creek, 8,500 feet above sea level. It is doubtful if any other State can afford a variety of climatological data equal to that recorded at these stations.

Though there may be a greater average seasonal snowfall in some of the uninhabited and unstudied portions of the United States, the records obtained in the high Sierra Nevada of California have not been exceeded. Particularly is this true of the region adjacent to the line of the Southern Pacific Railroad which connects Sacramento, Cal., with Reno, Nev. Throughout many square miles in the Sierras traversed by this line more than 100 inches of unmelted snow falls every winter, making it the region of heaviest known snowfall in the United States. The Snow and Ice Bulletin published weekly by the Weather Bureau throughout the winter does not include data from this region, as it does not attempt to show the depth of the snow in the mountains except as reported by the regular Weather Bureau stations. The average seasonal snowfall and the average annual precipitation for 19 of the cooperative stations located in this region of excessive snowfall are given in Table 1.

As indicated in Table 1, the snowfall stations are all located at high levels. Those located on the eastern slopes of the mountains are drained by streams which empty into mountain lakes. Those on the western slopes are in the watersheds of streams all of whose waters eventually reach San Francisco Bay via the Sacramento and San Joaquin rivers. At most of these stations the average annual precipitation is moderate to heavy. During 1904, 136 inches of precipitation was recorded at Bowman's Dam, while in 1909, 141 inches occurred at La Porte. While the summers are relatively dry and the winters relatively wet throughout the State of California, the seasonal periodicity is less marked in the mountains than elsewhere. Though thunderstorms are not often

experienced along the immediate coast, they occur occasionally in the higher parts of the State and furnish what little rain falls during the summer half-year. It is apparent from Table 1 that up to a certain height there is an increase in the total annual precipitation with increase of elevation. Precipitation records covering 40 years are now available at stations extending along the line of the Southern Pacific Company from Sacramento, whose elevation is 71 feet and mean annual precipitation 19.40 inches, to Summit, whose elevation is 7,017 feet and mean annual precipitation 48.07 inches. These show that up to a height of about 6,500 feet there is an average increase of about 0.9 inch of rainfall with every 100 feet increase of height above sea level, the rate of increase being greatest between the 3,000- and 4,000-foot levels. Beyond the 6,500-foot level the rate of increase becomes negative; that is, the mean annual precipitation decreases with height. It should be added that these mountains, though regions of heavy rainfall and excessive snowfall, are not perpetually covered with snow. On the highest peaks the snow disappears in May or June, and usually does not reappear until October. Snowstorms occasionally occur late in the spring, however. For example, 18 inches of snow fell at Blue Canyon on May 6, 1890.

TABLE 1.—Average seasonal snowfall and average annual precipitation at high stations in northern California.

Station.	County.	Watershed.	Feet above sea level.	Number of years' record.	Average seasonal snowfall.	Average annual precipitation.
					In.	In.
Bishop Creek.....	Inyo.....	Mountain lakes.....	8,500	5	167.7	
Blue Canyon.....	Placer.....	Sacramento.....	4,095	14	207.2	74.2
Boca.....	Nevada.....	Mountain lakes.....	5,531	29	151.5	29.8
Bowman's Dam.....	do.....	Sacramento.....	5,500	17	272.7	75.6
Cisco.....	Placer.....	do.....	5,929	33	370.0	52.0
Crocker's.....	Tuolumne.....	San Joaquin.....	4,452	4	113.2	55.0
Emigrant Gap.....	Placer.....	Sacramento.....	5,230	29	282.7	
Fordyce Dam.....	Nevada.....	do.....	6,500	16	402.4	72.4
Greenville.....	Plumas.....	do.....	3,600	18	100.2	44.0
Lake Eleanor.....	Tuolumne.....	San Joaquin.....	4,700	5	158.6	
Lake Spaulding.....	Nevada.....	Sacramento.....	4,600	17	223.5	78.5
La Porte.....	Plumas.....	do.....	5,000	17	284.3	89.2
Quincy.....	do.....	do.....	3,400	18	76.6	48.4
Sumnerdale.....	Mariposa.....	San Joaquin.....	5,270	13	141.9	55.1
Summit.....	Placer.....	Sacramento.....	7,017	44	419.6	48.1
Susanville.....	Lassen.....	Mountain lakes.....	4,195	22	78.7	21.8
Tamarack.....	Alpine.....	San Joaquin.....	8,000	8	521.3	57.5
Truckee.....	Nevada.....	Mountain lakes.....	5,819	35	195.1	27.1
Yosemite.....	Mariposa.....	San Joaquin.....	3,945	8	106.9	38.6

If the records of a single station for one winter are considered, it is doubtful if greater seasonal snowfalls have been recorded in this country than those presented in Table 2 below.

TABLE 2.—Some maximum winter snowfalls.

Place.	Winter.	Depths.		
		Inches.	Feet.	Meters.
Summit, Cal. (Donner post office).....	1879-80	783	65.25	19.89
Do.....	1889-90	776	64.66	19.71
Tamarack, Cal.....	1910-11	757	63.08	19.23

To the average reader the enormity of these figures is perhaps best realized when he translates them to feet. Partly because of the length of the record and partly because of the extreme depth of snow, the seasonal snowfall for Summit, Cal., for a period of 44 years is reproduced herewith in Table 3. An idea of the winter landscape at Summit may be had from figure 7 opposite.

TABLE 3.—Seasonal snowfall at Summit, Cal.

[Lat., 39° 19' N.; long., 120° 10' W. Elevation, 7,017 feet.]

Winter.	Snowfall.	Winter.	Snowfall.	Winter.	Snowfall.
	Inches.		Inches.		Inches.
1870-71	300	1885-86	462	1900-1901	440
1871-72	550	1886-87	422	1901-2	373
1872-73	334	1887-88	345	1902-3	407
1873-74	200	1888-89	261	1903-4	434
1874-75	284	1889-90	776	1904-5	375
1875-76	525	1890-91	335	1905-6	514
1876-77	178	1891-92	380	1906-7	602
1877-78	341	1892-93	634	1907-8	340
1878-79	446	1893-94	511	1908-9	442
1879-80	783	1894-95	685	1909-10	342
1880-81	154	1895-96	544	1910-11	563
1881-82	492	1896-97	560	1911-12	277
1882-83	296	1897-98	292	1912-13	281
1883-84	482	1898-99	481	1913-14	437
1884-85	202	1899-1900	406	Average	419.6

Furnishing, as it does, most of the water that is used for irrigation purposes in California, the snow of the high Sierras is sometimes aptly referred to as the life blood of the State. The farmer is greatly interested because he wishes to know in advance how much water there is available to grow the coming season's crops. The hydraulic engineer, using water for power purposes, is interested for obvious reasons. The hydraulic miner also was until recently interested in the amount of snow. The railroad engineer, concerned with the maintenance of way, is also involved, as the task of keeping a track clear under conditions of such excessive snowfall is not an easy one. (See figs. 2, 6, 10, 12, opposite p. 218.) To the average visitor to this region, however, the amount of snow on the ground is a most impressive sight. Based upon the records of the past nine years, the average amount of snow on the ground at three selected stations is given in Table 4.

TABLE 4.—Average amount of snow on ground at three California stations on the dates mentioned.

Dates.	Fordyce dam (6,500 ft.).	Summit (7,017 ft.).	Tamarack (8,000 ft.).
	Inches.	Inches.	Inches.
Dec. 1.....	8	9	19
Dec. 15.....	27	20	40
Jan. 1.....	42	44	62
Jan. 15.....	76	82	115
Feb. 1.....	88	122	165
Feb. 15.....	94	126	173
Mar. 1.....	99	127	183
Mar. 15.....	100	140	194
Mar. 31.....	101	118	192

## THE MEASUREMENT OF SNOW.

It is not the purpose of this paper to discuss the merits of the various methods of measuring snow. For a discussion of that subject the reader is referred to Weather Bureau instrument division Circular E, entitled "Measurement of Precipitation," by Prof. C. F. Marvin. It is sufficient to say that the accurate measurement of precipitation falling in the form of snow is an exceedingly difficult problem, and one which has not yet been satisfactorily solved.

Particularly is this true when the snowfall is heavy. It should therefore be borne in mind that some of the snow data here given are subject to correction. The depths of snow quoted herewith are in inches of unmelted snow. Permanently installed stakes bearing snow scales marked in inches are used at Summit, Cal., and at Blue Canyon, Cal., the lengths of these scales being 20 feet and 12 feet, respectively. At Blue Canyon the depth of newly fallen snow is also measured by means of a stick and a canvas snow mat which serves as a plane of measurement. Given a level area, therefore, and one on which the snow is evenly deposited without the inequalities resulting from wind action, the measurement of the depth of the snow on the ground is comparatively simple.

However, the complete measurement of precipitation falling in the form of snow involves a measurement of the water content of the snow. Since the usually adopted ratio of 10 parts of snow being equivalent to 1 part of water is only occasionally true it is apparent that the fundamental problem is that of a proper "catch" of the snow in a suitable instrument. Its subsequent conservation and measurement is not a very difficult matter. The wind is the most troublesome of the disturbing factors. Regarding this problem Prof. Marvin has laid down the following general propositions:

1. In calm and very light winds all gages of reasonable form and dimensions and in similar locations catch sensibly true and equal depths of precipitation.
2. In moderate, brisk, and high winds the catch of gages not screened or protected becomes more and more deficient with the increase in the force of the wind.
3. The deficit in catch due to wind is greater for snow than for rain.
4. In collecting *rain* the deficit in catch, even in strong winds, can be reduced to a relatively small percentage by the use of appropriate wind shields, fences, and other protective barriers, such as have been successfully employed by Nipher, Hellmann, and others.
5. Additional careful experimentation is needed to perfect and improve wind shields and to demonstrate that gages so protected collect snow satisfactorily on windy occasions.

At Blue Canyon and at Summit the Marvin shielded rain-and-snow-gage has been in use for several years. (See fig. 11.) In this instrument, which is 9 feet in height, the collector consists of a cylindrical can, 42 inches deep by 10.85 inches inside diameter, around the mouth of which there is a double arrangement of wind shields. To make a measurement the collector is hung upon a spring balance whose dial has been altered to read directly in inches and hundredths of water (or melted snow), a tare allowance being made for the empty collector. At Blue Canyon the gage has given reasonably satisfactory results, the only difficulty experienced being due to the fact that wet, sticky snow sometimes adheres to the inside top portion of the collector. On one occasion during the past winter a sheet of frozen snow formed completely across the mouth of the collector, while on six other occasions there formed an annular sheet of such width that the "catch" was appreciably deficient. At Summit, on the other hand, the gage, even though constructed in the massive proportions given above, has proved inadequate properly to measure the excessive snowfall. (See fig. 7.) There snow accumulates on the ground to a depth of 20 feet almost every winter; on March 10, 1911, 25 feet 7 inches of snow covered the ground. These measurements are made on level ground, and are not in drifts or banks. It is apparent that a gage of huge proportions



FIG. 1.—Snow fields near the summit of the Sierra Nevada.



FIG. 2.—Southern Pacific Company snowsheds near Emigrant Gap, Cal., in winter.



FIG. 3.—Street scene in Hobart Mills, Cal., in winter.



FIG. 4.—One-story cottages buried to the eaves by snow.



FIG. 5.—Headwaters of Truckee River, near Emigrant Gap, Cal.



FIG. 6.—Snow fields and railroad snowsheds near Cisco, Cal.



FIG. 7.—Summit Hotel at Summit, Cal. (Donner post office), March 18, 1911. A three-story building whose first story is buried under the 26 feet of snow covering.



FIG. 8.—Winter scene at Hobart Mills, Cal., near Truckee, Cal. Row of one-story houses buried in the level snow.

is demanded in snow of so great a depth. When the writer went officially to inspect this station on March 4, 1915, it was with some difficulty that he located the gage, as it was completely submerged in the snow, its topmost point being 19 inches below the snow surface.

The density rather than the depth of the snow is, after all, the important matter. The water content, both of newly fallen snow and of that on the ground at any one time, is the information desired by most people. For new snow the Marvin shielded gage, referred to above, is perhaps the most satisfactory instrument yet devised. For determining from time to time the water available in snow remaining on the ground many and various methods have been tried.

Investigators agree that a desirable method is to carefully weigh an accurately measured volume. Mr. G. H. Willson,<sup>1</sup> section director for California, has long been of the opinion that the best method of determining the water available in snow on the ground is to secure the mean weight of a cubic foot of snow throughout a vertical section of the snow cover. His conclusions have the hearty approval of many engineers and other practical men interested in this problem. In theory the method is perfect. In practice, however, great difficulties are encountered, and the method is not recommended for general use. It is inapplicable when the snow is soft, the consistency of the snow rendering it impossible to get cubes. Moreover, in any kind of snow care is required to form perfect cubes, exactly 1 foot in every dimension, in order to produce reliable results. Furthermore, the method is exceedingly laborious, particularly when the snow is deep, and it often requires more time than the cooperative observers care to give to the work.

The method of measuring the weight of a pailful of snow, reading the density directly on a suitably marked spring balance, and then multiplying the depth of the layer by the density thus determined, has some advantages. But when the snow is deep and has within it ice strata or layers of varying density, as is frequently the case, considerable labor is involved in securing the true average density with the snow pail. The method of cutting out and measuring tubular sections<sup>2</sup> has been used successfully by Prof. J. E. Church, of the University of Nevada, in extensive observations in the Sierras in snow 20 to 30 feet deep. Prof. Church introduced the use of the spring balance for effecting the measurements and otherwise improved the whole apparatus. In California there is a growing demand among mountain snowfall observers for some practicable accurate method of measurement.

#### CONDITIONS ACCOMPANYING HEAVY SNOWFALL.

It might be contended that the data of heavy snowfall here given are based upon measurements made in canyons and gulches, where the wind has transported the snow, and the figures are therefore misleading. This is not true, however. During the past winter, at a time when 192 inches of snow covered the ground at Summit, eight measurements of the depth of snow on level ground at widely separated points on the mountains in the vicinity of the station were made, with the result that the depths varied only from 190 to 194 inches—that is, but 2 inches on each side of that at Summit. It should also be stated that, as its name indicates, Summit is located at the very apex of the mountains, at the highest point on this branch of the Southern Pacific Railroad. While the exposure is not exactly that of a peak, there is no point in the vicinity more than a few hundred feet higher than the level plot where the snow measurements are made. As a matter of fact the winds at these elevated stations are always relatively light and are in marked contrast with velocities recorded

at high stations in the northeastern part of the United States. Based upon the 3 p. m. (Pacific time) observations telegraphed daily to the San Francisco office, the air at Summit was absolutely calm on 44 of the 90 days, or 49 per cent of the time constituting the first three months of 1915. The extremely high wind velocities which often occur in winter in the White Mountains of New Hampshire are unknown in the Sierra Nevada of California. The difference in velocities is probably explained by the difference in distance from storm tracks, the White Mountains being closely adjacent to the numerous storms passing down the St. Lawrence Valley, while the Sierra of California is hundreds of miles south of most storms, and the intervening area is one of uneven topography. As further evidence of the absence of strong wind accompanying snowfall in the Sierras the following is given: When the writer inspected the station at Blue Canyon on March 3, 1915, he observed that the ground under the pine and spruce trees in the vicinity was perfectly bare, while 60 inches of snow covered the ground elsewhere.

By actual measurement a circular area 9 feet 7 inches in radius was found under a large pine tree to be entirely free from snow, while all about it the snow was 5 feet deep. The snow, falling in straight lines through practically calm air, is caught by the branches and when the sun reappears later it melts and the drops of water fall to the ground there melting the small amount of snow that may have accumulated.

#### PRESSURE RESULTING FROM DEEP SNOW.

To one who has never observed snow of greater depth than 4 or 5 feet, the pressure exerted by a snow cover 15 to 25 feet in depth is almost beyond comprehension. One might naturally infer that the pressure sustained by any object submerged in the snow is simply that of a vertical section of the snow above it. While this may be true for freshly fallen snow of superficial depth it is not true for deep snow which has been deposited in installments and which has intermittently been subjected to freezing and thawing, as is the case in the high Sierras. The following examples of the tremendous pressure of deep snow will suffice: The Marvin shielded rain-and-snow-gage at Summit (see fig. 7), though substantially constructed of steel and sheet iron, was found to be a complete wreck when it was dug out of the snow on March 4 last. In the language of the observer, "It appeared as though a cyclone [i. e., tornado] had struck it." The wind shields had been completely stripped off by the weight of the snow, the guy wires were broken, and the collector had been forced off its pedestal and was lying on the ground beneath. At Blue Canyon a fence, recently built around the railway station, had for its horizontal bars some discarded locomotive boiler flues, 2 inches in diameter. These tubes, made of a good quality of steel, were about 8 feet in length. When the heavy snow came, the vertical pressure it exerted upon these horizontal bars was so great that they were bent to such an extent that they fell to the ground from their sockets in the wooden posts.

The great pressure exerted upon submerged objects by deep snow is worthy of further consideration. It appears that when the sun emerges after a heavy snowfall the surface stratum is partially melted but freezes to a hard crust after sunset. As this process is repeated day after day and the snow decreases in depth, irregularities appearing on the surface show that the snow over most submerged objects melts less rapidly than elsewhere. Humps on the snow surface usually mark the positions of objects beneath. When freezing of the surface stratum follows the

<sup>1</sup> See remarks by Mr. Willson at end of this paper.

<sup>2</sup> See Prof. Henry's remarks at end of this paper.

noonday thaw, the weight of the frozen crust is borne by the submerged object, not only the crust directly over it, but also that for many square feet in every direction. More snow falls and the increased weight must be borne by the object beneath. The process is repeated over and over again, and if the snow becomes sufficiently deep the submerged object is either crushed or forced to the ground. A vertical post deeply submerged in snow is in some respects like a toadstool, in that it must sustain the weight of a large disk which rests horizontally upon the top of its vertical axis.

#### THE ECONOMICS OF DEEP SNOW.

It is readily apparent that snow of so great a depth as that which falls in the Sierra Nevada Mountains must profoundly affect the economics of that region. Of these influences the most interesting perhaps are those affecting the railroads and their operation. In order to operate during the winter months, the Southern Pacific Company has found it necessary to construct 32 miles of snowsheds between Blue Canyon and Truckee, at a cost of \$42,000 a mile over single track and \$65,000 a mile over double track. (See figs. 2, 6, and 9.) On an average, \$150,000 a year is spent for upkeep and renewals, the expenditure for 1914 having been \$65,000 for repairs and \$91,000 for renewals. The average life of a shed is 22 years. They are built of massive timbers and are designed to sustain snow 16 feet in depth. When the snow gets deeper than 16 feet it must be shoveled off by hand. At certain points where the railway is located along steep slopes thousands of tons of snowslide over the tops of the sheds every winter. At these places a kind of apron, technically known as a "backoff," 30 to 40 feet in length, is built on the upslope side of the shed in order that the snow may slide harmlessly over the top. Even though timbers 12"×14" in cross section were used in its construction, 48 feet of snowshed near Blue Canyon collapsed because of the weight of the snow on February 15, 1915. The fire hazard is naturally great. For fire-fighting apparatus four trains in summer and two trains in winter are kept under constant steam. All local engines carry pumps, and are followed by tank cars filled with water for fire-fighting purposes. Concrete snowsheds have been built on other railroads to offset the fire hazard, but their initial cost renders that form of construction almost prohibitive. One other feature of this region is noteworthy. Flat-roofed houses are conspicuous through their absence. The gables of all houses, and particularly dwellings, are built at sharp angles in order that the snow may slide off easily.

#### HISTORICAL INFLUENCES.

Needless to add, the deep snows of the high Sierras have played a part in the history of the State of California. While the mountains themselves acted as a barrier, the deep snows made them well nigh impassable for about six months of the year. One incident in the early history of California is significant in this connection. For several years preceding the discovery of gold in California in 1848, there had been an increasing number of settlers coming from all over the continent. In the summer of 1846 the influx had been unusually large, several hundred immigrants having come via Truckee, along the route now marked by the Southern Pacific Railroad. The Donner party, consisting of 83 persons, accompanied by a numerous caravan of "prairie schooners," cattle, etc., had been delayed by mishap and dissension en route. On October 31, 1846, they

started the steep ascent on the eastern side of the Sierras. A few days later, when they had advanced no farther than a small lake (now known as Donner Lake) but a few miles from Truckee, a typical winter storm brought snow of so great a depth that the horses and cattle were submerged and frozen, and the party was cast into despair at the prospect of spending a winter without shelter or provisions. The deeper snow of the higher altitudes rendered advancement almost impossible, while retreat appeared to be hopeless. The garrison at one of the California forts, anticipating the distress of the Donner party, sent two Indians with provisions for its relief. When, in midwinter, the food supply again ran low, a group of 22 desperate men, known to posterity as the "Forlorn Hope," started to cross the summit of the mountains. Of these, but 7 eventually reached the fertile Sacramento Valley. \* \* \* Death also reduced the number of those encamped at the lake. From time to time other parties attempted the apparently impossible feat of crossing the mountains. On February 19, 1847, 22 feet of snow covered the ground in the vicinity of the camp. When succor finally came in the late winter, but two men were found alive. \* \* \* Of the 83 who started the ascent the preceding October, 42 perished during the fateful winter. The story of the privations of the Donner party is one of the most pitiful tales in American history.

Modern methods of transportation have now eliminated the barrier of the snows. In the construction of the various railroads, engineering feats of high order were necessary to contend with previously unheard of depths. While the part played by the snow is not so spectacular at the present time as it was during the days of the pioneer, the influence is none the less important. Modern practices have changed the snow that was formerly an impediment to progress, into one of the valuable resources of the Commonwealth of California.

#### DISCUSSION.

1. The method of cutting out a tubular section of snowfall and determining the water content by melting was suggested in 1882, in Instructions for Voluntary Observers of the Signal Service, Washington, 1882, page 74; but the practical application of the idea of determining the water equivalent of snowfall on the ground by weighing a tubular section was first worked out by Mr. Robert E. Horton at Utica, N. Y., in the winter of 1903-4 (Monthly Weather Review, 33: 196.) Later the method was successfully used by the Weather Bureau on the recommendation of Prof. H. C. Frankenfield, and apparatus to carry out the idea was devised by Prof. C. F. Marvin, as described in Instrument Division Circular E (3d ed.), Measurement of Precipitation. Prof. J. E. Church, jr., of the University of Nevada, Reno, Nev., introduced the use of a spring balance and otherwise developed the apparatus, especially with reference to its use in very deep snow banks, such as are found in the Sierra Nevada. Prof. Church's apparatus is described and illustrated in the Quarterly Journal of the Royal Meteorological Society (London) for January, 1914, also in Meteorologische Zeitschrift for January, 1913, and in Scientific American Supplement for September 7, 1912.

The most efficient and accurate apparatus for the purpose of determining the snow density where the depths are not excessive is doubtless that devised by Mr. B. C. Kadel, while in charge of the experiment station maintained jointly by the Forest Service and the Weather Bureau at Wagon Wheel Gap, Colo., in 1911.

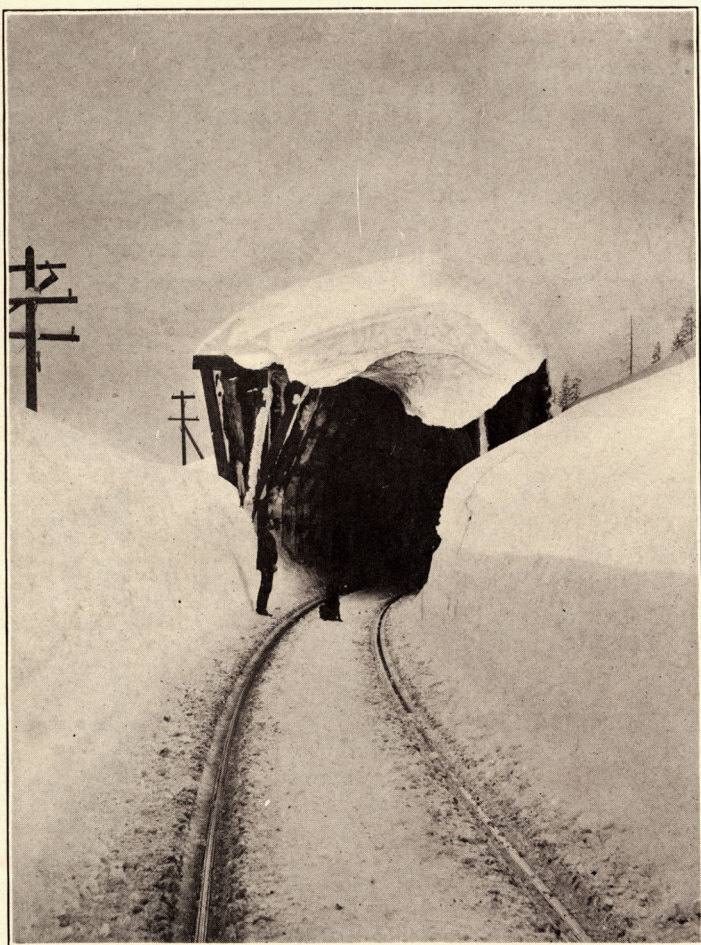


FIG. 9.—Entrance to Southern Pacific Company's snowsheds, Blue Canyon, Cal., 1889-90. Snow is 165 inches deep on the level.



FIG. 10.—Blue Canyon, Cal., during the winter of 1893-94.

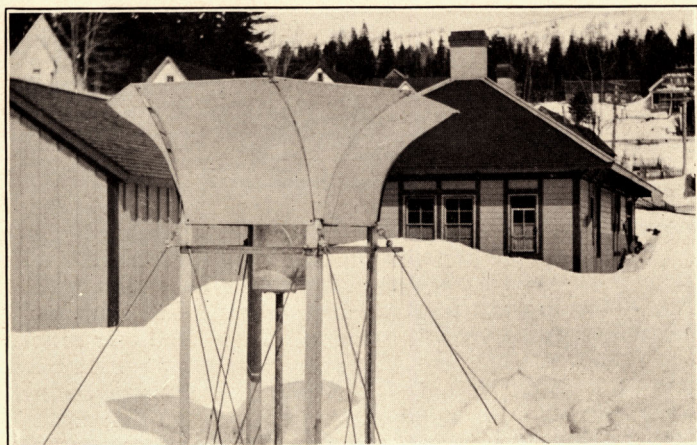


FIG. 11.—The Marvin shielded rain-and-snow gage in operation at Blue Canyon, Cal.



FIG. 12.—A railroad push plow clearing the tracks of the Southern Pacific Company near Hobart Mills, Cal. Note depths at side of cleared tracks.

